State of the Art (SOTA)
Manual for Stationary Gas Turbines

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State of New Jersey
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Air Quality Permitting Program

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Manual for Stationary Gas Turbines
Section 3.14

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3.14.i ABBREVIATIONS

BACT	Best Available Control Technology
CFR	Code of Federal Regulations
CO	Carbon Monoxide
DLN	Dry low NOx combustor technology
DB	Duct Burner
EPA	Environmental Protection Agency
HHV	High Heating Value
HRSG	Heat Recovery Steam Generator
LAER	Lowest Achievable Emission Rate
MM BTU	Million British Thermal Units
N.J.A.C.	New Jersey Administrative Code
NOx	Nitrogen Oxides
NSPS	New Source Performance Standards
PM10	Particulate Matter equal or smaller than 10 microns in diameter
PPMVD	Parts Per Million Dry Volume
PSD	Prevention of Significant Deterioration of Air Quality (40 CFR 52.21)
SCR	Selective Catalytic Reduction
SI	Steam Injection system
SNCR	Selective Non-Catalytic Reduction
SOTA	State -of- the- Art
SO_2	Sulfur Dioxide
TSP	Total Suspended Particulates
VOC	Volatile Organic Compounds
WI	Water Injection system

3.14 SOTA MANUAL FOR STATIONARY GAS TURBINES

3.14.1 Scope

3.14.1.1. Applicability and Determination of SOTA

If an application proposes construction, installation, reconstruction, or modification of equipment and control apparatus which is a significant source identified in N.J.A.C. 7:27-8, the applicant is required to document state of the art (SOTA) for the source with potential to emit any HAP at a rate equal to or greater than the SOTA threshold in Appendix 1, Table B; or with a potential to emit any other air contaminant or category of air contaminant at a rate equal to or greater than the SOTA threshold in Appendix 1, Table A of N.J.A.C. 7:27-8.
SOTA must be documented as follows:
1. For an air contaminant subject to LAER (Lowest Achievable Emission Rate) requirements pursuant to N.J.A.C. 7:27-18, compliance with LAER requirements for that air contaminant represents SOTA. LAER is a case by case determination.

2. For an air contaminant subject to BACT (Best Available Control Technology) requirements pursuant to 40 CFR 52.21, compliance with BACT requirements represents SOTA. BACT is a case-by-case determination.

3. For an air contaminant that is a HAP, emitted by equipment for which MACT (Maximum Achievable Control Technology) requirements have been promulgated in 40 CFR Part 63, compliance with MACT requirements represents SOTA;

4. For an air contaminant emitted by equipment for which New Source Performance Standards (NSPS) have been promulgated on or after August 2, 1995, compliance with NSPS represents SOTA;

5. For an air contaminant not subject to 1 through 4 above, SOTA shall be documented through one of the following options. The applicant may choose which option to pursue:

i. An applicant shall document compliance with a SOTA Manual that applies to the source;
ii. If the source is eligible for a general permit under N.J.A.C. 7:27-8.8, an applicant shall register for the general permit in accordance with N.J.A.C. 7:27-8.8; or
iii. An applicant shall document compliance with a case by case SOTA standard determined through the process detailed in N.J.A.C. 7:27-8.12.

State of the Art (SOTA) performance levels outlined below apply to newly constructed and reconstructed (please refer to the definition of “Reconstruct” or “Reconstruction” in N.J.A.C. 7:27-22, Operating Permits and N.J.A.C. 7:27-8 for non-major source permits) stationary gas turbines with heat input capacity greater that 10 million BTUs per hour (HHV basis). For air pollution control permit applications for modifications to an existing stationary gas turbine, determination of emission levels and air pollution control technologies that represent advances in the art of air pollution control will be performed on a case-by-case basis.

3.14.1.2. Description for stationary gas turbine design and different operating cycles.

A gas turbine is an internal combustion engine that operates with rotary motion. In stationary applications, the hot gases are directed through one or more fan-like turbine wheels to generate shaft horsepower. In larger facilities the heat form the exhaust gases may be recovered through add-on heat exchangers or other devices. Three primary sections of a gas turbine include the compressor, combustor, and turbine. The compressor draws in ambient air and compresses it to approximately 30 times ambient pressure. The compressed air is then directed to the combustor section, where fuel is introduced, ignited and burned. There are three types of combustors: annular, can-annular and silo. An annular combustor type is a single continuous chamber roughly the shape of the doughnut that rings the turbine in a plane perpendicular to the air flow. The can-annular type uses a similar configuration but is a series of can-shaped chambers rather than a single continuous chamber. The silo combustor type is one or more chambers mounted external to the gas turbine body. Following the combustors, hot gases are diluted with additional cool air from the compressor section and directed to the turbine section at temperature up to 1285 ^{o}C. Energy is recovered in the turbine section in the form of shaft horsepower of which greater than 50% is required to drive the internal compressor section.

The two types of turbine design are industrial and aero-derivative. Industrial turbines were designed to supply mechanical energy to industrial equipment, i.e., generators and compressors. The aero-derivative turbines are jet engines which have been converted to drive shaft based on the designs used in the aerospace industry.

The four basic operating cycles for gas turbines are simple cycle, regenerative cycle, cogeneration cycle, and combined cycle.

<u>Simple Cycle</u>

A gas turbine functions with only the three primary sections, compressor, combustor, and turbine. Simple cycle efficiency is typically in the 30-40 percent range. This cycle offers the lowest installed capital cost but also provides the least efficient use of fuel, therefore the highest operating cost.

Regenerative Cycle

This is essentially a simple cycle gas turbine with an added heat exchanger, called a recuperator which preheats the combustion air. In this cycle, thermal energy from the exhaust gases is transferred to the compressor discharge air prior to being introduced into the combustor.

Cogeneration Cycle

This is essentially a simple cycle gas turbine with an added exhaust heat exchanger, called a heat recovery steam generator. The steam is generated by the exhaust that can be delivered at a variety of pressure and temperature conditions to meet site specific thermal process requirements. Adding a heat recovery steam generator increases the capital cost, but also increases the overall cycle efficiency. Heat recovery steam generators can be with or without duct burners. Duct burners are used to combust fuel to generate more steam from heat recovery steam generators.

Combined Cycle

A combined cycle gas turbine is used to generate electric power. The gas turbine drives an electric generator, and the steam produced in the heat recovery steam generator is delivered to a steam turbine, which also drives an electric generator. Heat recovery steam generators can be with or without duct burners. Duct burners are used to combust fuel to generate more steam from heat recovery steam generators.

3.14.2 SOTA Performance Levels

The following table presents the SOTA performance levels for criteria pollutants (CO, VOC, and NOx) and control technologies for stationary gas turbines with heat input capacity greater than 10 MM BTU/hr (HHV basis). Also, in addition to criteria pollutants performance levels for ammonia (NH_3) and opacity have been addressed. No emission levels for SO_2, TSP, and PM-10 are specified. Permits for these sources will include limits for SO_2, TSP, and PM-10 developed based on the fuel type. Percentage sulfur by weight in liquid fuel must comply with N.J.A.C. 7:27-9.2 (Sulfur Content Standards) and N.S.P.S Subpart GG, whichever is more stringent.

3.14.3 Technical Basis

The performance levels listed in SOTA Performance Levels and Control Technology Table below are based on permit applications filed with the New Jersey Department of Environmental Protection, and data from the United States Environmental Protection Agency's RACT/BACT/LAER Information Systems and permit applications filed with other states.

SOTA Performance Levels and Control Technology Table

Pollutant	Heat Input Capacity MM Btu/hr (HHV Basis) for Turbine Only	Air Pollution Control Technology				Emission Rate - ppm vd @ 15% Oxygen			
		Natural Gas as Fuel*		No. 2 Fuel Oil as Fuel**		Combined Cycle ##		Simple Cycle # (for Heat Input Capacity)	
		Simple Cycle #	Combined Cycle ##	Simple Cycle #	Combined Cycle ##	Natural Gas as Fuel*	No. 2 Fuel Oil as Fuel **	Natural Gas as Fuel *	No. 2 Fuel Oil as Fuel **
NOx	10 - 100	WI, or DLN, or SCR, or combination of WI and DLN; or WI and SCR; or DLN and SCR; or OCR.	WI, or SI, or SCR, or DLN, or combination of DLN and WI; or DLN and SI; or SCR and DLN; or WI, DLN, and SCR; or SI, DLN, and SCR or OCR.	WI, or DLN, or combination of WI and DLN; or WI and SCR; or DLN and SCR or OCR.	WI or SI or SCR,or DLN, or combination of DLN and WI; or DLN and SI; or SCR and DLN; or WI, DLN, and SCR; or SI, DLN, and SCR or OCR.	25	65	25 (10-500 MMBtu/hr)	65 (10-100 MMBtu/hr)
	>= 100					3.5	3.5 [a]	15 (500-1000 MMBtu/hr) 9 (>1000 MMBtu/hr)	42 (>100 MMBtu/hr)
CO	10 - 100	Good combustion	Good combustion	Good combustion	Good combustion	50 [b]	50 [b]	50 [b]	50 [b]
	>= 100	Good combustion or CO oxidation catalyst	Good combustion or CO oxidation catalyst	Good combustion or CO oxidation catalyst	Good combustion or CO oxidation catalyst	5 [b, c]	5 [b, c]	15[b]	15 [b]
VOC	10-100	Good combustion	Good combustion	Good combustion	Good combustion	25 [d]	25 [d]	25 [d]	25 [d]
	> =100	Good combustion	Good combustion	Good combustion	Good combustion	10 [d]	10 [d]	10 [d]	10 [d]
Ammonia Slip	all turbines with SCR	---	---	---	---	10	10	10	10
Opacity	all turbines	Good combustion	Good combustion	Good combustion	Good combustion	Please refer to note "e" for opacity standards			

* - Natural gas or any other gaseous fuel (Butane, refinery gas, digester gas, etc.)
** - No.2 fuel, or Aviation Kerosene, or low sulfur distillate oil
# - Emission limits and air pollution control technologies shall be the same for simple cycle or regenerative cycle turbines.
- Emission limits and air pollution control technologies shall be the same for combined cycle or cogeneration cycle turbines.
WI - Water injection system
SI - Steam injection system
DLN - Dry low NOx combustor technology
SCR - Selective catalytic reduction technology
OCR - Other Catalytic Reduction Technologies such as Selective catalytic reduction technology without ammonia injection or Flameless catalytic combustion system with low catalyst temperature to achieve low NOx and CO levels.
a - If the gas turbine is combusting liquid fuel during periods of gas curtailment or during any other unavoidable interruptions, state of the art performance level for NOx is 42 ppmvd at 15% oxygen.
b - During low load operating scenario (<30% of base load capacity), CO emissions shall not exceed 250 ppmvd at 15% oxygen.
c - For combined cycle turbine without duct burner, state of the art performance level for CO is 15 ppmvd at 15% oxygen.
d - During low load operating scenario (<30% of base load capacity), VOC emissions shall not exceed 50 ppmvd at 15% oxygen.
e - Opacity Standards:
10% - During gaseous fuel burning, except during start-up, shutdown, and fuel transfer periods (exclusive of visible condensed water vapor, for a period of no more than 10 consecutive seconds).
20% - During start-up, shutdown, fuel transfer periods and liquid fuel burning (exclusive of visible condensed water vapor, for a period of no more than 10 consecutive seconds).

NOTE:

Compliance averaging times for NOx, CO, and VOC performance levels are 3 hours rolling on one hour block basis (if Continuous emissions monitors are required) or an average of three one hour stack emissions tests. Compliance for SO_2, TSP and PM-10 emissions shall be based on average of three one hour stack emission tests.

3.14.4 Control Technologies For Stationary Gas Turbines (Pollution Prevention and Post - Combustion Control)

3.14.4.1 NOx Formation

NOx is formed in the combustion turbine through fuel NOx formation and thermal NOx formation. Fuel NOx is formed when nitrogen compounds in the fuel combine with oxygen present in the combustion zone to form NOx. Fuel NOx can be reduced by reducing the amount of nitrogen in the fuel (burning lower fuel-bound nitrogen fuel such as natural gas) and/or by reducing the amount of excess oxygen in the combustion zone. Thermal NOx is formed when nitrogen from the combustion air combines with oxygen in the combustion zone at temperatures in excess of 2100 degrees Fahrenheit to form NOx. Thermal NOx can be reduced by reducing the amount of oxygen in the combustion zone and/or lowering the temperature in the combustion zone (lowering flame temperature).

3.14.4.2 NOx Control Technologies

Reductions in NOx, CO and VOC emissions can be achieved using combustion control technologies or flue gas treatment (post-combustion control technologies).

a) Combustion Control Technologies for NOx

Combustion control technologies listed below are pollution prevention techniques. By controlling the most important factors effecting combustion chemistry (temperature, excess oxygen and residence time) these techniques are effective in minimizing the formation of pollutants. Pollution prevention techniques also include using lean fuels and improved combustion efficiency (i.e., cogeneration and combined cycle systems).

i. Wet Controls [water injection (WI) or steam injection (SI)]

Water injection or steam injection is a technology to reduce or limit thermal NOx formation by reducing the combustion turbine flame temperature. Water/steam is injected into the turbine combustors, which mixes in the flame with the combustion by-products, and reduces flame temperatures by dilution and cooling of combustion by-products. The result is a lower flame temperature and consequently reduced formation of thermal NOx. Injection rates for both water and steam are usually described by a water/steam-to-fuel ratio and are usually given on a weight basis. The water/steam-to-fuel injection ratio is the most significant factor affecting the performance of wet controls. Higher ratios result in greater NOx reductions, but also may increase emissions of CO and hydrocarbons, may reduce turbine efficiency, and may increase turbine maintenance requirements.

ii. Dry Low NOx Combustors (DLN)

Combustion modifications that lower NOx emissions without wet injection include lean combustion, reduced combustor residence time, lean premixed combustion, and two-stage rich-lean combustion.

- Lean Combustion

An equivalence ratio of 1.0 indicates a stoichiometric ratio of fuel and air. Equivalence ratios below 1.0 indicate fuel-lean conditions. With lean combustion, the additional excess air cools the flame, which reduces the peak flame temperature and reduces the rate of thermal NOx formation.

- Reduced Combustor Residence Time

In all gas turbine combustor designs, the high temperature combustion gases are cooled with dilution air to an acceptable temperature prior to entering the turbine. With reduced residence time combustors, dilution air is added sooner than with standard combustors. Because the combustion gases are at a high temperature for a shorter time, the amount of thermal NOx formation decreases.

- Lean Premixed Combustors

In a lean premixed combustor design, the air (A) and fuel (F) is premixed at very lean A/F ratios prior to introduction into the combustion zone. The excess air in the lean mixture lowers combustion temperature, which greatly reduces NOx formation rates. Lean premixed combustion is not as effective in reducing NOx levels if high nitrogen fuels are fired.

- Rich/Quench/Lean Combustion (RQL)

RQL combustors burn fuel-rich in the primary zone and fuel-lean in the secondary zone. Incomplete combustion under fuel-rich conditions in the primary zone produces an atmosphere with a high concentration of CO and hydrogen gas (H_2). The CO and H_2 replaces some of the oxygen for NOx formation and also acts as a reducing agent for any NOx formed in the primary zone. Thus fuel nitrogen is released with minimal conversion to NOx. The lower peak flame temperatures due to partial combustion also reduces the formation of thermal NOx. Both thermal and fuel NOx are controlled with this design.

iii. Flameless Catalytic Combustion System

This system is a way to carry out combustion to minimize the formation of NOx while achieving low CO and unburned hydrocarbon levels. The system is totally contained within the combustor of the gas turbine. The combustor consists of four sections:

-The pre-burner (to start-up and acceleration of the engine).
-The fuel injection and fuel/air mixing system
-The catalyst module, where a portion of the fuel is combusted without a flame to maintain low temperature gas.
-The homogeneous combustion region, where the remainder of the fuel is combusted.

The overall combustion process in the Flameless Catalytic Combustion system is a partial combustion of fuel in catalyst module followed by completion of the combustion downstream of the catalyst. The partial combustion within the catalyst produces no NOx. Homogenous combustion produces only 1-2 ppm NOx because the combustion occurs at a uniformly low temperature.

b) Post Combustion Control Technologies

i. Selective Catalytic Reduction (SCR)

SCR is an add-on NOx control technique that is placed in the exhaust stream following the gas turbine. SCR is a process in which ammonia is directly injected into the flue gas and then passed over a catalyst to react with NOx, converting the NOx and ammonia to nitrogen and water. This reaction normally requires higher temperatures in order to take place. However, the catalyst allows this reaction to take place at a lower temperature than would be required without it (approximately 570 ^{O}F to 750 ^{O}F depending on the catalyst used). The catalyst is usually either a noble metal, base metal (titanium or vanadium), or a zeolite based material.

ii. The Catalytic Absorption System Without Ammonia Injection

This system utilizes a single catalyst for the removal of both carbon monoxide and nitrogen oxide emissions. The catalyst works by simultaneously oxidizing CO to CO_2, NO to NO_2, and then absorbing NO_2 onto its surface through the use of a potassium carbonate absorber coating. These reactions are shown below, and are referred to as the "Oxidation/Absorption Cycle".

$$CO + 1/2\, O_2 \rightarrow CO_2$$
$$NO + 1/2O_2 \rightarrow NO_2$$

$$2NO_2 + K_2CO_3 \rightarrow CO_2 + KNO_2 + KNO_3$$

The CO_2 in reaction (1) and reaction (3) is exhausted up the stack. Note that during this cycle, the potassium carbonate coating reacts to form potassium nitrites and nitrates, which are then present on the surface of the catalyst. When the surface of the catalyst becomes saturated with NO_x the catalyst must enter the regeneration cycle. The regeneration cycle is accomplished by passing a dilute hydrogen reducing gas across the surface of the catalyst in the absence of the oxygen.

c) CO and VOC Control Technology (Pollution Prevention and Post Combustion Control)

i. Combustion Controls (Pollution Prevention)

Combustion controls involve optimizing the factors effecting combustion chemistry (i.e., temperature, excess oxygen and residence time) to minimize emissions of CO and other incomplete combustion products as well as NO_X in a balanced manner. (See above for details).

ii. Oxidation Catalyst (Post Combustion Control)

Oxidation catalyst can be used to reduce emissions of CO and VOC. For effective reduction of CO and VOC the flue gas must be lean (excess Oxygen) to promote the following reactions:

$$CO + O_2 \text{-------}> CO_2$$
$$HCx + O_2 \text{-------}> H_2O + CO_2$$
$$H_2 + O_2 \text{---------}> H_2O$$

The operating temperature window is between 500 ^{O}F - 1100 ^{0}F. There are several precious metal catalysts available to reduce emissions of CO and VOC.